Composite Structures 135 (2016) 83–95

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Bi-level dominance GA for minimum weight and maximum feasibility robustness of composite structures

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ARTICLE INFO

Article history:
Available online 18 September 2015

Keywords:
Multi-objective optimization
Composite structures
Minimum weight
Feasibility robustness
Bi-level dominance

ABSTRACT

In the proposed approach the robust design optimization (RDO) of composite structures is addressed as a bi-objective optimization problem with following objective functions: (1) the weight of the structure which optimality is associated with performance robustness; and (2) the variability of structural response which is associated with feasibility robustness of design constraints. The determinant of the variance–covariance matrix of the response is adopted for feasibility robustness assessment, being the sensitivities calculated by the adjoint variable method. The design and uncertainty rules are controlled by the following classes of variables and parameters: the deterministic design variables, the random design variables, and the random parameters.

To solve the RDO of composite structures an evolutionary algorithm, denoted by Bi-level Dominance Multi-Objective Genetic Algorithm (MOGA-2D) is proposed. The Pareto front is built using a hierarchical structure where evolution is based on the exchange data between two populations: a small population using local dominance and elitism and an enlarged population to store the non-dominated solutions. The numerical tests show the capabilities of the approach. Although the optimal Pareto front establishes the trade-off between performance and robustness, knowledge on the importance of each uncertainty source can help the designer to make a decision on design space.

1. Introduction

Composite materials behavior is affected by numerous uncertainties that should be considered in structural design. The problem of design-based uncertainty of laminated composite structures can be formulated as an optimization problem under reliability constraints or addressed as the problem of alleviating the effects of unavoidable system parameter uncertainties. The first perspective is associated to reliability-based design optimization (RBDO) and the second one is considered in robust design optimization (RDO). Both strategies depend on uncertainty propagation analysis of composite structures response and different length scales. However, there are conceptual differences between the referred two formulations. The RBDO cover optimal design problems under given constraints of catastrophic failure probability in rare extreme events, while RDO emphasizes the search design on minimizing the structural response sensitivity with respect to uncertain variations in system parameters or allows for maximum possible system variability in any service conditions. In this work, the focus of proposed approach is based on RDO concepts.

In theoretical developments of RDO, both the robustness of design objectives and the robustness of design constraints are usually studied, conceptually denoted by performance robustness and feasibility robustness. The goal of robust design is to optimize the mean performance commonly known as optimality, and minimize the variability of the performance function known as robustness as suggested by Huang and Du [1], Zaman et al. [2] and Ragavajhala and Mahadevan [3]. Thus, each performance function corresponds to two objectives in RDO problem formulation to be optimized simultaneously [1–3]. Nevertheless, another concept of robustness can be defined as the maximization size of the deviations from the target design that can be tolerated, whereby the product satisfies all requirements as proposed by Salazar and Rocco [4]. This design rule is based on the concept such as the response variability does not necessarily have to be minimized but rather that it be bounded. So, the design with largest tolerance to the input uncertainty is considered as the robust design. The authors extend the work to multi-objective optimization based on two or more conflicting objectives [4].

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http://dx.doi.org/10.1016/j.compstruct.2015.09.019
0263-8223/

RDO applied to composite structures under probabilistic constraints is a very important field due to uncertainties associated with physical or geometric properties of fiber-reinforced composites. Merrill Lee et al. [5] studied the effect of laminate stacking on the robustness of stiffened panels for aerospace applications and compare the experimental results obtained using damage tolerant design and robust design concepts. Few RDO approaches considering together the performance and the response variability of composite structure can be found in literature. Choi et al. [6] proposed an approach based on searching the stacking sequence of laminated composite structures which, corresponds to the less sensitive performance properties relatively to uncertainties in the input parameters. This perspective follows RDO concepts where the objective is to minimize the effects of uncertainty on optimal design. The same strategy based on considering the statistical data in objective and constraint functions is also used by Conceição António and Hoffbauer [7] combining reliability and robustness. In DongSeeop Lee et al. [8] proposed approach the objectives are to minimize the total weight, normalized mean displacement and the standard deviation of the displacement of hybrid composite structures, considering critical load cases.

The important parts for robustness assessment composite laminated structures are the uncertainty and sensitivity analysis [9–11]. A number of approaches to uncertainty and sensitivity analysis, including differential analysis, response surface methodology, Monte Carlo analysis, and variance decomposition procedures can be found in literature [12–15]. The almost totality of sensitivity analyses in applications with composite structures used local importance measures of uncertainty on input system parameters or design variables [9,16,17]. A study driven by António and Hoffbauer [10] shows that a first order local method is acceptable to analyse the uncertainty propagation on response for angle-ply laminates. Furthermore, an obvious advantage of local methods in robustness assessment is the reduced computational costs of the associated uncertainty analysis.

In this paper, the RDO problem formulation for composite structures is based on two objectives to be minimized: (1) the weight of the structure which optimality is associated with structural performance robustness; and (2) the variability of structural response which is associated with the feasibility robustness, measured on stress and displacement design constraints. A first order local method based on determinant of the variance–covariance matrix of the response is adopted for the feasibility robustness assessment.

The use of multiple objective evolutionary algorithms (MOEAs) in robust design of systems has been reported by few publications found in literature [4], [18–20]. Most of the referred approaches are based on dominance concepts to build the Pareto front proposed by Deb [21]. To solve the RDO of composite laminated structures a bi-objective optimization procedure based on previous author developments [22] is adopted in the proposed approach of this paper. The Pareto front is built using a hierarchical genetic algorithm with co-evolution of populations, denoted by MOGA-2D. In this algorithm the evolution is based on the exchange data between two populations: a small population using local dominance and elitism and an enlarged population to store the non-dominated solutions. A self-adaptive genetic search incorporating Pareto dominance and an elitist strategy storing the non-dominated solutions found during the evolutionary process is considered [22]. The paper is organized as follows: a brief composite shell structures modeling description and the structural response analysis are given in Section 2. The characterization of uncertainty propagation on structural response based on sensitivity analysis and the measures of constraint feasibility for composite structures are also introduced in Section 2. The RDO problem formulation for composite shell structures and the proposed MOGA-2D evolutionary algorithm are presented in Section 3. The computational results and the discussion are presented in Section 4 and the conclusions are established in Section 5.

2. Uncertainty propagation on composites structures

Robust design optimization (RDO) of composite structures is commonly based on aleatory uncertainty [1,5–11,16,17]. Aleatory uncertainty arises from inherent randomness in the behavior of the laminated composite structure system under study. In this work the quantification of response uncertainties of composite structures due to uncertainty in the physical or geometric properties and loads of the structural model is implemented based on linear statistical analysis. This methodology uses a Taylor's series expansion to obtain a linear relationship between the response random output variables - displacements and stresses, and the random structural input parameters or design variables [9–15]. The adjoint variable method is used to obtain the sensitivity matrix [9,23]. This method is appropriated for composite structures due to the large number of random input parameters.

2.1. Analysis of structural response

The structural analysis of laminated composite structures is based on the shell finite element model developed by Ahmad [24] and further improvements [25]. This shell element is obtained from a 3-D finite element using a degenerative procedure. It is an isoparametric element with eight nodes and five freedom degrees per node based on the Mindlin shell theory. The shell consists of a number of perfectly bonded plies. Each individual ply is assumed homogeneous and anisotropic.

The displacement vector at each kth node is.

$$\delta_k = (u_k, v_k, w_k, \beta_{1k}, \beta_{2k}) \tag{1}$$

with three independent translations u_k, v_k, w_k and two independent rotations β_{1k}, β_{2k}. The displacement vector of the element is

$$\boldsymbol{\delta}^e = (\delta_1, \ldots, \delta_k, \ldots, \delta_n) \tag{2}$$

being n the number of degrees of freedom of the element. The displacement field in the ith element can be expressed as

$$\mathbf{u}_i = \sum_{k=1}^{n} \left(N_k(\xi,\eta)\mathbf{u}_{ik}^{mid} + N_k(\xi,\eta)\frac{1}{2}\zeta h_k[\bar{\mathbf{v}}_{1k}\bar{\mathbf{v}}_{2k}](\beta_{1k},\beta_{2k})^T \right) \tag{3}$$

where $N_k(\xi,\eta)$ are the shape functions, (ξ,η,ζ) is the local curvilinear coordinate system being ξ and η defined in the middle plan of the shell element and ζ is the coordinate associated to the thickness direction. In Eq. (3) $\mathbf{u}_{ik}^{mid}$ is the displacement vector of the kth node referred to the middle surface of the shell, h_k is the thickness defined by upper and lower surfaces of the shell at the kth node and $\bar{\mathbf{v}}_{1k}$ and $\bar{\mathbf{v}}_{2k}$ are the cosines of the nodal coordinate system associated to the middle surface.

The stress and strain are referred to local coordinate system (X', Y', Z') related with the surface ζ taken as constant. The strain vector is

$$\boldsymbol{\varepsilon}' = \begin{Bmatrix} \varepsilon'_x \\ \varepsilon'_y \\ \gamma'_{xy} \\ \gamma'_{xz} \\ \gamma'_{yz} \end{Bmatrix} = \begin{Bmatrix} \frac{\partial u}{\partial x'} \\ \frac{\partial v}{\partial x'} \\ \frac{\partial u}{\partial y'} + \frac{\partial v}{\partial x'} \\ \frac{\partial u}{\partial z'} + \frac{\partial w}{\partial x'} \\ \frac{\partial w}{\partial y'} + \frac{\partial v}{\partial z'} \end{Bmatrix} \tag{4}$$

In general it can be written the following strain–displacement relationship:

$$\boldsymbol{\varepsilon}' = \mathbf{Bu} \tag{5}$$